The Optical Gravitational Lensing Experiment. Red Clump Stars as a Distance Indicator*

A. U d a l s k i

Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
e-mail: udalski@astrouw.edu.pl

ABSTRACT

We present relation of the mean *I*-band brightness of red clump stars on metallicity. Red clump stars were proposed to be a very attractive standard candle for distance determination. The calibration is based on 284 nearby red giant stars whose high quality spectra allowed to determine accurate individual metal abundances. High quality parallaxes ($\sigma_\pi/\pi < 10\%$) and photometry of these very bright stars come from Hipparcos measurements. Metallicity of the sample covers a large range: $-0.6 < \mathrm{[Fe/H]} < +0.2$ dex. We find a weak dependence of the mean *I*-band brightness on metallicity ($\approx$0.13 mag/dex).

What is more important, the range of metallicity of the Hipparcos sample partially overlaps with metallicity of field giants in the LMC, thus making it possible to determine the distance to the LMC by almost direct comparison of brightness of the local Hipparcos red clump giants with that of LMC stars. Photometry of field red clump giants in nine low extinction fields of the LMC halo collected during the OGLE-II microlensing survey compared with the Hipparcos red clump stars data yields the distance modulus to the LMC: $(m-M)_{\mathrm{LMC}} = 18.24 \pm 0.08$ mag.

1 Introduction

Paczyński and Stanek (1998, hereafter PS) noticed that the *I*-band absolute brightness, M_I, of red clump (hereafter RC) giants, the intermediate age (2–10 Gyr) helium core burning stars, has intrinsically small dispersion and can be used as a "standard candle" for distance determination. The obvious advantage of this method is large number of these stars in stellar populations allowing determination of the mean brightness with statistically unprecedented accuracy. Moreover, RC giants are also very numerous in the solar neighborhood. Therefore their brightness could be precisely calibrated with hundreds of stars for which the Hipparcos satellite measured parallaxes with accuracy better than 10% (Perryman *et al.* 1997). It should be noted

*Based on observations obtained with the 1.3 m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington.

that RC stars are the only standard candle which can be calibrated with direct, trigonometric parallax measurements. Similar quality parallaxes do not exist for Cepheids or RR Lyr stars (*cf.* Fig. 2 of Horner *et al.* 1999).

As in the case of any other stellar standard candle, the brightness of RC stars might, however, be affected by population effects: different chemical composition or age of the stellar system being studied, as compared to the local Hipparcos giants. PS argued that both dependences of $\langle M_I \rangle$ on age and metallicity are negligible. On the other hand, Girardi *et al.* (1998) claimed much stronger dependences based on theoretical modeling. According to their results $\langle M_I \rangle$ of RC stars could be different by as much as 0.5 mag in different environments. However, one should be aware that results of modeling are quite sensitive to the input physics and results from different types of evolutionary codes are not consistent each other (Dominguez *et al.* 1999, Castellani *et al.* 1999). While models seem to reasonably reproduce qualitative properties of RC stars they cannot provide accuracy of hundredths of magnitude required for precise distance determination.

The necessity of good, preferably empirical, calibration of population effects on RC brightness became very urgent, in particular when the distance modulus to the LMC was determined (Udalski *et al.* 1998, Stanek, Zaritsky and Harris 1998), supporting the "short" distance scale to that galaxy ($\approx$0.4 mag smaller than the "long" value of $(m-M)_{\rm LMC}=18.50$ mag). The distance to the LMC is one of the most important distances of the modern astrophysics because extragalactic distance scale is tied to it. Udalski (1998a) presented an empirical calibration of $\langle M_I \rangle$ of RC stars on metallicity suggesting only a weak dependence (0.09 ± 0.03 mag/dex). The dependence of $\langle M_I \rangle$ of RC stars on age was studied by Udalski (1998b). Observations of RC stars in several star clusters of different age located in low extinction areas of the Magellanic Clouds showed that their $\langle M_I \rangle$ in these clusters is independent of age (for stars 2–10 Gyr old) within observational uncertainties of a few hundredths of magnitude. Recently, Sarajedini (1999) presented analysis of a few Galactic open clusters suggesting fainter RC in older ($>$5 Gyr) clusters.

In this paper we present empirical arguments which additionally support usefulness of the "RC stars" method – the relation of $\langle M_I \rangle$ *vs.* metallicity based on the most precise data necessary to solve the problem: high resolution and S/N spectra of nearby red giants, for which accurate parallaxes and photometry were measured by Hipparcos. Large range of metallicity of nearby RC giants partially overlapping with metallicity range of field RC giants in the LMC enables us to compare brightness of these stars and de-

termine the RC distance modulus to the LMC largely free from population uncertainties.

2 Observational Data

The sample of red giant stars from the solar neighborhood comes from the Hipparcos catalog and consists of objects with high accuracy trigonometric parallaxes ($\sigma_\pi/\pi < 10\%$). About 75% stars from this sample are the same objects which were used by PS, *i.e.*, stars with I-band photometry. To enlarge that data set we have also included stars which I-band magnitude was obtained from $B-V$ color *via* very well defined correlation between $B-V$ and $V-I$ colors (*cf.* Fig. 8 Paczyński *et al.* 1999), *i.e.*, stars marked as type 'H' in the Hipparcos catalog. While accuracy of the I magnitude of these stars is somewhat worse, it is still acceptable taking into account usually larger uncertainty from parallax error.

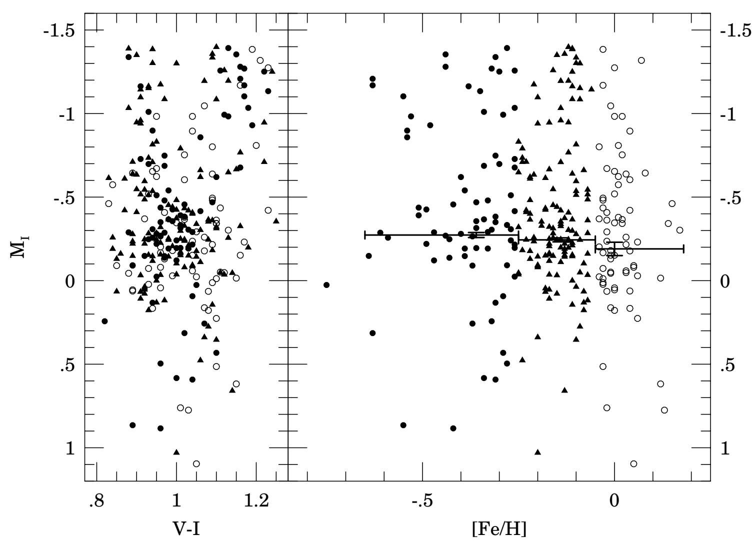

Fig. 1. M_I of 284 nearby red giants with precise photometry and spectroscopy plotted as a function of $V-I$ color (left panel) and metallicity [Fe/H] (right panel). Stars of low, medium and high metallicity are marked by filled circles, filled triangles and open circles, respectively.

For further analysis only the stars with [Fe/H] abundance determination were selected. We used results of the spectroscopic survey of McWilliam (1990), containing [Fe/H] determinations for 671 G and K giants based on

high resolution ($R \approx 40000$) and S/N (≈ 100) spectra. This is the most comprehensive and homogeneous data set available. Typical accuracy of [Fe/H] determination is about 0.1 dex. 284 objects from our photometric sample were cross-identified with objects in the spectroscopic survey list of McWilliam (1990). Left panel of Fig. 1 presents the color-magnitude diagram (CMD) of this sample. Comparison with Fig. 2 of PS indicates that full photometric sample and our 284 object sample used for further analysis are distributed identically in the CMD, so we did not introduce any significant bias when limiting Hipparcos stars to objects with spectroscopic data. The mean distance from the Sun of our final sample of 284 stars is $<d>=66$ pc. It is worth noting that due to accurate Hipparcos parallaxes the possible Lutz-Kelker bias of the absolute magnitude of our sample is negligible, as shown by Girardi *et al.* (1998).

The photometric data of the LMC fields were obtained during the OGLE-II microlensing survey (Udalski, Kubiak and Szymański 1997). Observations were collected with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile which is operated by the Carnegie Institution of Washington on eight photometric nights between October 30, 1999 and November 12, 1999. Single chip CCD camera with 2048×2048 pixel SITe thin chip was used giving a scale of 0.417 arcsec/pixel. $3-5$ frames in the V and I-bands were collected for each field with exposure time of 300 sec for both bands. Photometry was derived using the standard OGLE pipeline. On each night several standard stars from the Landolt (1992) fields were observed for transformation of the instrumental magnitudes to the standard system. The error of zero points of photometry should not exceed 0.02 mag.

3 Discussion

3.1 Hipparcos Red Clump Stars

CMD of the analyzed sample of red giants presented in the left panel of Fig. 1 indicates that the majority of objects are RC stars that form a very compact structure located in the range: $0.0 < M_I < -0.5$ and $0.9 < V-I < 1.1$. They are, however, contaminated by red giant branch stars and a blue vertical structure, going from $M_I \approx -1.4$ mag down to $M_I \approx 0.1$ mag, consisting of younger (more massive) red giants.

M_I of stars is plotted against metallicity [Fe/H] in the right panel of Fig. 1. The distribution of stars is non-uniform with most objects within metallicity range of $-0.3 <$ [Fe/H] < 0.0 dex. To investigate the relation

of M_I of RC stars on metallicity we divided our sample into three subsamples: high metallicity, $[\mathrm{Fe/H}] > -0.05$ dex, medium metallicity, $-0.25 < [\mathrm{Fe/H}] < -0.05$ dex, and low metallicity stars, $[\mathrm{Fe/H}] < -0.25$ dex. Such a division ensures more or less uniform distribution of objects within each bin with the mean, median and mode values equal to $(0.02, 0.00, 0.00)$, $(-0.15, -0.14, -0.14)$ and $(-0.39, -0.36, -0.33)$ dex for the high, medium and low metallicity bins, respectively. We determined $\langle M_I \rangle$ in all bins in similar manner as described in Udalski *et al.* (1998). Fig. 2 presents the histograms of distribution of M_I for each subsample with fitted Gaussian function representing RC stars superimposed on parabola representing background stars.

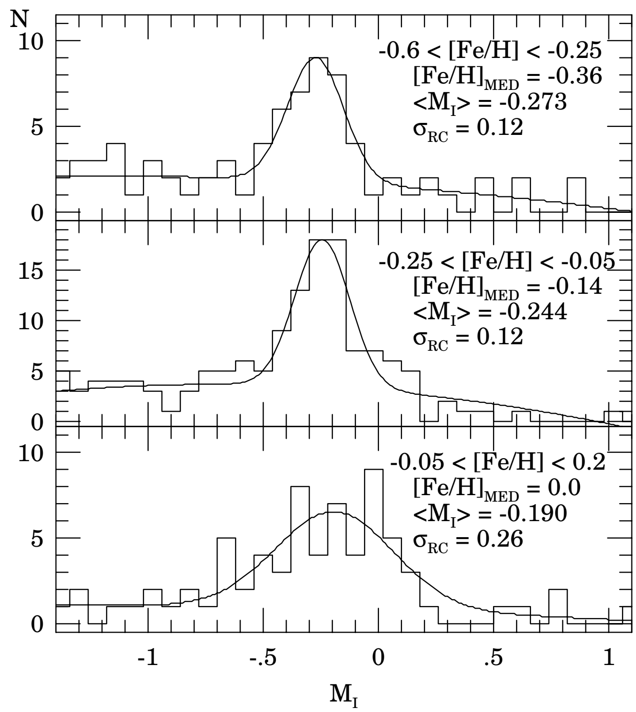

Fig. 2. Histograms of distribution of M_I of the low (top panel), medium (middle panel) and high metallicity sample (bottom panel) of local RC stars. Bins are 0.07 mag wide.

It is evident from Fig. 2 that the majority of stars in the low and medium metallicity bins are typical intermediate age RC objects. Small dispersion of their M_I ($\sigma_{\mathrm{RC}} = 0.12$ mag) indicates that these stars can indeed be a good standard candle. On the other hand the high metallicity bin has the RC poorly defined ($\sigma_{\mathrm{RC}} = 0.26$ mag). Closer examination of Fig. 1 indicates that

most of stars from this bin (open circles) are red branch giants and objects located on the vertical sequence of younger giants in the RC evolution phase with very few stars belonging to the intermediate age RC.

$\langle M_I \rangle$ of RC stars in the low, medium and high metallicity bins are equal to $-0.273 \pm 0.015, -0.244 \pm 0.012$ and -0.190 ± 0.041 mag, respectively (statistical error). The horizontal bars in the right panel of Fig. 1 show the range of each bin and its $\langle M_I \rangle$. The vertical bars are shown at the median metallicity of each bin and represent statistical uncertainty of $\langle M_I \rangle$. It is clear from Figs. 1 and 2 that the absolute brightness of RC stars increases with lower metallicity. If we consider all three bins then the slope of the M_I *vs.* [Fe/H] relation is about 0.2 mag/dex. One should, however, remember that the high metallicity bin is poorly defined due to small number of metal rich RC stars of intermediate age in the solar neighborhood. Moreover, metallicity of the most metal rich stars from McWilliam's sample is very likely underestimated (McWilliam 1997) making this bin additionally uncertain. Larger mean metallicity of this bin would lead to smaller slope of the M_I *vs.* [Fe/H] relation. Indeed, if we limit ourselves only to low and medium metallicity bins where the intermediate age RC stars dominate the linear relation becomes:

$$M_I = (0.13 \pm 0.07) \cdot ([\mathrm{Fe/H}] + 0.25) - (0.26 \pm 0.02) \tag{1}$$

Eq. (1) indicates that the dependence of M_I on metallicity is rather weak. The relation is in good agreement with the previous empirical determination by Udalski (1998a) based on comparison of RC stars with RR Lyr stars but this time it is based on precise measurements of numerous sample of individual stars, thus it is more reliable. It should be also stressed that the result is weakly sensitive to systematic errors, as those are very unlikely in the Hipparcos absolute photometry of so bright and nearby stars, and due to weak dependence on metallicity even large systematic metallicity error (which is also unlikely, Taylor 1999) would only lead to a magnitude shift of the order of a few hundredths of magnitude.

3.2 LMC Red Clump Stars

Table 1 summarizes the basic properties of field RC stars in nine fields around star clusters distributed in different parts of the LMC halo. The interstellar extinction in these directions is small, thus minimizing uncertainties of extinction-free photometry. All lines-of-sight are far enough from the LMC center so the reddening could be reliably determined from the

Table 1

Photometry of field red clump stars in the LMC

Direction	$\langle I \rangle$	σ^{STAT}	σ_{RC}	N_{stars}	$E(B-V)$	$\langle I_0 \rangle$	[Fe/H]
SL8	18.197	0.008	0.148	1345	0.105	17.991	−0.35
SL509	18.039	0.007	0.127	784	0.029	17.982	−0.50
SL262	18.037	0.019	0.138	223	0.026	17.986	−0.50
SL842	18.001	0.021	0.130	157	0.054	17.895	−0.55
SL388	18.053	0.009	0.114	749	0.042	17.971	−0.60
SL862	18.143	0.009	0.150	1063	0.119	17.910	−0.60
OHSC33	18.081	0.013	0.155	660	0.100	17.885	−0.65
SL817	18.112	0.008	0.143	1427	0.101	17.914	−0.70
IC2134	18.116	0.007	0.105	864	0.078	17.963	−0.70

COBE/DIRBE maps of Schlegel, Finkbeiner and Davis (1998). The I-band interstellar extinction was calculated using the standard extinction curve ($A_I = 1.96 \cdot E(B-V)$). We assumed uncertainty of the reddening value equal to ± 0.02 mag.

$\langle I \rangle$ of RC stars was derived in similar manner as in Udalski *et al.* (1998). About 160–1400 field red giants were used for its determination in our fields. Statistical uncertainty of $\langle I \rangle$ is usually below 0.01 mag so the main contribution to the extinction free magnitude, $\langle I_0 \rangle$, error budget comes from the interstellar reddening uncertainty. Dispersion of brightness of field RC stars, σ_{RC}, is typically below 0.15 mag similar to the local RC stars.

Unfortunately metallicity of the LMC field RC stars is not known so precisely as that of the Hipparcos local giants. Metallicity of field giants in our nine lines-of-sight was determined by Bica *et al.* (1998, herafter BGDCPS) using Washington photometry. It ranges from -0.7 dex to -0.35 dex (Table 1) with typical error of 0.1 dex of internal determination, and the total error of ≈ 0.2 dex. Due to large errors it is not clear if the observed dispersion of metallicity in different parts of the LMC is real or results from the uncertainty of the method. It is also not clear whether the absolute numbers are correct, *e.g.*, metallicity determined using the same method for several LMC clusters by BGDCPS is on average by ≈ 0.2 dex lower than spectroscopic metallicities of the LMC clusters determined by Olszewski *et al.* (1991). This point should be cleared up in the near future with direct

spectroscopic observations of the LMC RC stars with new 8-m class telescopes.

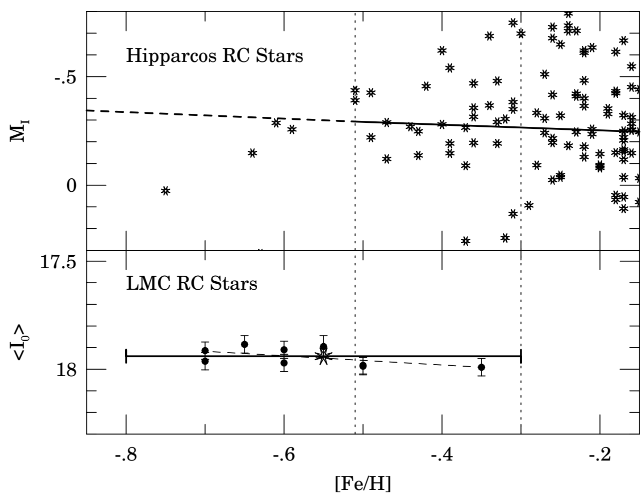

Fig. 3. M_I of Hipparcos RC giants (upper panel) and $\langle I_0 \rangle$ of RC stars in nine fields in the LMC (lower panel) plotted as a function of metallicity. Asterisk in the lower panel denotes the mean metallicity of RC stars in the LMC and the horizontal bar spread of metallicity. Dotted lines indicate the range where metallicities of the local and LMC stars overlap. Solid thick line in the upper panel marks the derived relation of M_I on [Fe/H] (Eq. 1) while dashed line is its continuation resulting from Girardi's (1999a) models. Dashed line in the lower panel indicates possible relation for the LMC RC stars.

Lower panel of Fig. 3 presents $\langle I_0 \rangle$ of RC stars in our fields in the LMC as a function of BGDCPS [Fe/H]. Large asterisk indicates the mean metallicity and brightness of the entire sample. Horizontal bar corresponds to the typical range of metallicities of field giants, ≈ 0.5 dex, as determined by BGDCPS. It is worth noting that if one assumes that dispersion of metallicity in the LMC fields is real and BGDCPS determinations are correct, at least differentially, then the observed trend of variation of $\langle I_0 \rangle$ with [Fe/H] is similar to the local sample of RC stars. The formal fit of a straight line gives the slope equal to 0.21 ± 0.12 mag/dex. Although one should treat this figure with caution it is encouraging that it is in good agreement with that resulting from analysis of the local RC stars.

3.3 Distance Modulus to the LMC

The range of metallicities among nearby RC stars is wide and covers $-0.6 <$ [Fe/H] $< +0.2$ dex. This is a very fortunate situation, because this range

partially overlaps at the low [Fe/H] end with metallicity of the RC stars in the LMC. In the upper panel of Fig. 3 M_I of Hipparcos RC stars is plotted as a function of [Fe/H]. Solid line marks relation of M_I *vs.* [Fe/H] given by Eq. (1). Two dotted vertical lines indicate the range where metallicities of the LMC and local Hipparcos RC stars overlap. We remind here that we have adopted BGDCPS metallicities of the LMC RC stars, and if they are too low, what is likely, the overlap of metallicities of both populations can be much larger.

The mean metallicity of the LMC RC stars lies outside the overlap region. Therefore, to derive $(m-M)_{\rm LMC}$ we have to slightly extrapolate M_I *vs.* [Fe/H] relation given by Eq. (1). $\langle M_I\rangle$ of the Hipparcos RC giants extrapolated to the metallicity of -0.55 dex is equal to $\langle M_I\rangle=-0.30\pm0.04$ mag. With $\langle I_0\rangle=17.94\pm0.05$ mag of RC stars in our nine lines-of-sight in the LMC, this immediately leads to $(m-M)_{\rm LMC}=18.24\pm0.08$ mag.

Can this result be severely affected by extrapolation? That could only be possible if M_I *vs.* [Fe/H] relation of RC stars for metallicities in the range of $-0.9<[\mathrm{Fe/H}]<-0.5$, *i.e.*, not covered by Hipparcos stars, would behave extraordinarily. In particular it would have to be extremely steep in this range to narrow the gap between our result and the "long" distance modulus of $(m-M)_{\rm LMC}=18.50$. However, this is not the case: we already mentioned that if dispersion of metallicity in the LMC fields as measured by BGDCPS is real then the slopes of M_I *vs.* [Fe/H] relations in the LMC and the local sample are similar. Also theoretical modeling of RC provides similar arguments. For instance, models of Girardi (1999a, Fig. 4) indicate that for RC stars of age 2–8 Gyr the mean slope of the M_I *vs.* [Fe/H] relation in the range of metallicities of $-1.0<[\mathrm{Fe/H}]<-0.4$ is about 0.15 mag/dex in excellent agreement with our empirical data (theoretical relation is plotted with dashed line in the upper panel of Fig. 3 as a continuation of our empirical relation). Thus large uncertainty of the distance modulus due to extrapolation of Eq. (1) is very unlikely.

Possible differences of ages of both populations can be another potential source of uncertainty of the derived $(m-M)_{\rm LMC}$. Empirical study of this effect based on analysis of clusters in the Magellanic Clouds showed that it is practically negligible for RC stars of age within 2–10 Gyr (Udalski 1998b). On the other hand analysis of a few Galactic open clusters by Sarajedini (1999) suggests that RC stars older than $\approx$5 Gyr become fainter. Without going into detailed discussion of these results we only note here that analysis of Galactic clusters requires very precise distance determination what is difficult and that two old clusters claimed to have fainter RC (Be39,

NGC188) have actually very sparse population of RC stars consisting of only a few stars. However, despite differences which deserve further studies, both Udalski (1998b) and Sarajedini (1999) data show that for the age range of 2–5 Gyr $\langle M_I \rangle$ of RC giants is constant within ± 0.05 mag. The age of the LMC RC stars is within this range (BGDCPS) and the vast majority of the local RC stars are younger than 4 Gyr (Girardi 1999b). To be on the safe side we included to the final error budget uncertainty of ± 0.05 mag for possible differences of age between both populations. We may conclude that the derived distance modulus to the LMC is largely free from population uncertainties. Also small interstellar extinction assures that the result is sound. Had there been any additional LMC extinction in the LMC fields, on top of that given by Schlegel *et al.* (1998), $(m-M)_{\rm LMC}$ would be reduced to even smaller value.

Acknowledgements. We would like to thank the anonymous referee whose critical remarks allowed us to significantly improve the manuscript. We are very grateful to Mr. K. Żebruń for collecting observations of the LMC fields. We thank Drs. B. Paczyński, K.Z. Stanek, M. Kubiak and M. Szymański for many discussions and important suggestions. The paper was partly supported by the grants: Polish KBN 2P03D00814 and NSF AST-9820314.

REFERENCES

Bica, E., Geisler, D., Dottori, H., Clariá, J.J., Piatti, A.E., and Santos Jr, J.F.C. 1998, *Astron. J.*, **116**, 723 (BGDCPS).

Castellani, V., Degl'Innocenti, S., Girardi, L., Marconi, M., Prada Moroni, P.G., and Weiss, A. 1999, *Astron. Astrophys.*, in press, astro-ph/9911432.

Dominguez, I., Chieffi, A., Limongi, M., and Straniero, O. 1999, *Astrophys. J.*, **524**, 226.

Girardi, L., Groenewegen, M.A.T, Weiss, A., and Salaris, M. 1998, *MNRAS*, **301**, 149.

Girardi, L. 1999a, *MNRAS*, **308**, 818.

Girardi, L. 1999b, astro-ph/9912309.

Horner, D. *et al.* 1999, astro-ph/9907213.

Landolt, A.U. 1992, *Astron. J.*, **104**, 372.

McWilliam, A. 1990, *Astrophys. J. Suppl. Ser.*, **74**, 1075.

McWilliam, A. 1997, *AAR&A*, **35**, 503.

Olszewski, E.W., Schommer, R.A., Suntzeff, N.B., and Harris, H.C. 1991, *Astron. J.*, **101**, 515.

Paczyński B., and Stanek, K.Z. 1998, *Astrophys. J. Letters*, **494**, L219 (PS).

Paczyński B., Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Soszyński, I., Woźniak, P., and Żebruń, K. 1999, *Acta Astron.*, **49**, 319.

Perryman, M.A.C. *et al.* 1997, *Astron. Astrophys.*, **323**, L49.

Sarajedini, A. 1999, *Astron. J.*, **118**, 2321.
Schlegel, D.J., Finkbeiner, D.P., and Davis, M. 1998, *Astrophys. J.*, **500**, 525.
Stanek, K.Z, Zaritsky, D., and Harris, J. 1998, *Astrophys. J. Letters*, **500**, L141.
Taylor, B.J. 1999, *Astron. Astrophys. Suppl. Ser.*, **135**, 75.
Udalski, A., Kubiak, M., and Szymański, M. 1997, *Acta Astron.*, **47**, 319.
Udalski, A. 1998a, *Acta Astron.*, **48**, 113.
Udalski, A. 1998b, *Acta Astron.*, **48**, 383.
Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Woźniak, P., and Żebruń, K. 1998, *Acta Astron.*, **48**, 1.